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Trevor Zink

Loyola Marymount University

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Material Recycling and the Myth of Landfill Diversion

Trevor Zink[1] *and Roland Geyer*[2]

[1]*Department of Management, Loyola Marymount University, Los Angeles, California, USA*
[2]*Donald Bren School of Environmental Science and Management, University of California–Santa Barbara, Santa Barbara, California, USA*

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Summary

Proponents of material recycling typically point to two environmental benefits: disposal (landfill/incinerator) reduction and primary production displacement. However, in this paper we mathematically demonstrate that, without displacement, recycling can delay but not prevent any existing end-of-life material from reaching final disposal. The only way to reduce the amount of material ultimately landfilled or incinerated is to produce less in the first place; material that is not made needs not be disposed. Recycling has the potential to reduce the amount of material reaching end of life solely by reducing primary production. Therefore, the "dual benefits" of recycling are in fact one, and the environmental benefit of material recycling rests in its potential to displace primary production. However, displacement of primary production from increased recycling is driven by market forces and is not guaranteed. Improperly assuming all recycled material avoids disposal underestimates the environmental impacts of the product system. We show that the potential magnitude of this error is substantial, though for inert recyclables it is lower than the error introduced by improperly assuming all recycled material displaces primary material production. We argue that life cycle assessment end-of-life models need to be updated so as not to overstate the benefits of recycling. Furthermore, scholars and policy makers should focus on finding and implementing ways to increase the *displacement potential* of recyclable materials rather than focusing on disposal diversion targets.

Introduction

Material recycling has become an important policy goal and topic of scholarly investigation. Two primary environmental rationales for material recycling that pervade public and scholarly discourse are disposal reduction and reduction of virgin production from raw materials (Ackerman 1997).[1] It is commonly accepted in both scholarly literature and public discourse that material recycling reduces disposal by landfill or incineration by "diverting" end-of-life material to alternative productive uses (e.g., Ajayi and Oyedele 2017; Assamoi and Lawryshyn 2012; CalRecycle 2012; Morris 2017; Mueller 2013; Smith 2015). Landfill reduction was historically important due to perceived landfill capacity shortages (Ackerman 1997; Melosi 2004) but remains important today due to the significant methane and emissions from organic materials such as paper and textiles (e.g., Karanjekar et al. 2015; Levis et al. 2017; Rastogi et al. 2014; Sadasivam and Reddy 2014; Young et al. 2004), and leachate emissions of "dissolved organic matter, inorganic macro components, heavy metals, and xenobiotic organic compounds" (Kjeldsen et al. 2002). Increasingly, biowastes, which generate

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Address correspondence to: Trevor Zink, College of Business Administration, Loyola Marymount University, 1 LMU Drive, Los Angeles, CA 90045, USA. *Email:* trevor.zink@lmu.edu, *Web*: https://cba.lmu.edu/faculty/?expert=trevor.zinkphd

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higher levels of methane in landfills, are also being diverted from landfill to uses in agricultural fertilizer and energy (e.g., Demirbas 2011; Fatih Demirbas et al. 2011; Fodor and Klemeš 2012). In regions without modern solid waste management infrastructure or where humans may interact with landfills, their impact is even higher, and therefore the benefit of landfill avoidance is greater (e.g., Agamuthu and Fauziah 2011). An alternative disposal method to landfill is incineration, which has impacts in terms of bottom and fly ash, the latter of which is typically more toxic than the input waste (Ackerman 1997). Material recycling is thought to divert end-of-life waste away from both disposal options.

In the case of metals, glass, and many plastics, modern landfill emissions are low relative to the impacts of collecting, sorting, and reprocessing them (Wang et al. 2012; US EPA 2016), so under modern waste management techniques, the landfill avoidance rationale makes little sense. However, a second reason for recycling recognizes that far less energy and material inputs are required to collect and reprocess many (but not all) materials than to produce them from virgin inputs (Björklund and Finnveden 2005). In environmental assessment methodologies such as life cycle assessment (LCA), it has been assumed that collecting and recycling end-of-life materials prevents the production (and therefore the impacts) of similar materials from raw inputs and therefore also conserves finite resources. The theory is that the impacts of recycling are more than offset by displaced virgin production, reducing net impacts.[2]

In contrast to the traditional view, in this essay we argue that the perceived dual benefits are in fact one and the same. We demonstrate that material recycling does not automatically divert waste from disposal—we show that any material that is produced must eventually be disposed; recycling cannot alter that eventual fate. Rather, recycling only reduces disposal *if and to the extent that* it displaces primary production. If recycling fails to prevent primary production, for instance, by displacing other secondary materials or by expanding markets (Zink et al. 2015), it also will not prevent disposal—it will merely delay that fate.

In this paper, we first discuss the theoretical underpinnings of recycling, material markets, and inevitable disposal. We then demonstrate the effect of various recycling scenarios on ultimate disposal with four simple case studies. Next, we generalize the findings of the case studies in a series of equations that quantify waste generation, primary production, collection, recycling, and disposal as a function of collection rate, recycling yield, and displacement. To show the methodological implications of our findings, we quantify the size of the errors introduced by improperly assuming that recycling reduces disposal and compare that to the error of improperly assuming that recycling displaces primary production. Finally, we discuss how life cycle assessment methodology should be improved to incorporate these results and conclude with the encouraging idea that recycling that *does* prevent primary production also prevents disposal. The "dual benefits" of recycling therefore boil down to one. Unfortunately, primary production displacement is far from guaranteed. Thus, we argue that the real focus of recycling research and policy should not be on increasing collection rates but on ensuring that recycled material displaces primary production.

In this paper, we restrict the scope of material recycling to the reprocessing of discarded materials back into similar materials, such as the recycling of metals, plastics, glass, paper, and cardboard back into metals, plastics, glass, paper, and cardboard. Material recycling, thus defined, entails the possibility that the recycled material could be used instead of its primary version. We explicitly exclude the conversion of biogenic waste, such as food or yard waste, into compost, soil amendment, or mulch. Whether or not this could properly be called recycling, it is not within the scope of this paper. Using chipped wood waste as mulch would divert it from landfill regardless of whether it displaces the production of anything. Reprocessing biogenic waste into soil amendment or mulch also typically limits it to one additional use and could thus be considered dissipative reuse or repurposing.

Recycling, Inevitable Disposal, and Markets

Two realities affect recycling's effect on disposal (here taken to mean landfill and incineration, but the ideas we present could also be applicable to improper or informal disposal). The first is that materials will not be cycled indefinitely. The belief that recycling automatically diverts material from landfill ignores the fact that, even in the most ideal recycling cases, material degrades in quality, diminishes in quantity (yield loss), or both during each use and recovery (i.e., collection and reprocessing) cycle. For instance, recycled bottle-grade polyethylene terephthalate (PET) loses quality in terms of purity and intrinsic viscosity and is therefore often used for nonbottle uses such as fiber or wood replacements, or must be blended with virgin polymer to be suitable for stretch blow-molded applications (Kuczenski and Geyer 2010). In metal recycling, contamination and alloy mixing reduces secondary material quality and limits its potential applications (Reck and Graedel 2012). Paper recycling lowers fiber strength and length, degrading quality (Wang et al. 2012). As materials become further degraded through additional cycles, they eventually become unsuitable for any further use and must be discarded. Recycling processes cannot recover 100% of collected materials into useful outputs, whether due to quality degradation or process inefficiencies. This means that some portion of collected materials is discarded to landfill, incinerated, or lost to the environment during reprocessing.[3] Real-world yield loss varies widely, depending on the material and recovery technology. Literature estimates of actual recycling yield loss (defined as 1 minus the ratio of recovered material to collected material) range from 2% for aluminum (Boin and Bertram 2005) to 6% to 8% for steel (American Iron and Steel Institute 2003) and 18.5% for polyethylene terephthalate (PET) (Kuczenski and Geyer 2010). Haupt et al. (2017) estimate recycling yield loss in the Swiss waste management system of approximately 11% (cardboard), 15% (aluminum, tinplate, and PET), and 26% (paper).

The result is that any material that enters the recycling system cannot cycle indefinitely and must eventually exit to landfill or incineration. Thus, recycling waste delays but does not prevent its final disposal. The only way recycling can reduce the amount of material landfilled is to reduce the amount produced—in other words, to displace primary production.

This leads to the second, less appreciated, but more important reality, which is economic rather than physical. It has increasingly been recognized that recycled materials do not automatically displace primary production (Ekvall 2000; Geyer et al. 2015; Zink et al. 2015). Vadenbo and colleagues (2016), for instance, developed a recycling reporting framework that accounts for a number of factors that affect how much primary material is displaced, including economic factors. Recycled materials compete with primary counterparts and other substitutes on global markets. Price, industrial demand, available technology, and myriad other factors interact to inform the decisions of agents in these markets, and the result is that the effect of increased recycling on primary production is difficult to predict. Rather than displace primary production, increased recycling can instead displace secondary material of another type or lower overall material prices, expanding the total market size (Zink et al. 2015). Theoretically speaking, the conditions needed to achieve 100% displacement (completely inelastic supply and demand) are economically unrealistic in materials markets (Zink et al. 2015). One empirical estimate shows that increased aluminum recycling in the United States is unlikely to displace primary aluminum one to one (Zink et al. 2017).

In summary, limited cycling means that the only way to avoid the landfill is by displacing primary production, while limited displacement means that recycling's environmental benefits should not be taken for granted.

Case Study

A simple example will help to illustrate this conclusion: Suppose four hypothetical scenarios for the production, recycling, and disposal of an example Material X.

1. Scenario 1 assumes no recycling. Demand for Material X is fixed at ten units per period. All produced material is used for one period and then disposed.
2. Scenario 2 assumes that 50% of end-of-life Material X is collected. Eighty percent of this material is recovered as raw material; the rest must be disposed (this could be thought of as material degradation, yield loss, or both). Recycled material is assumed to fully displace primary material (displacement rate = 100%; recycling reduces primary production by the same amount). Recycled material reaching end of life is handled according to the same rates as primary end-of-life material.
3. Scenario 3 also assumes that 50% of end-of-life Material X is collected and also assumes that 80% of this is recovered as raw material. However, Scenario 3 assumes that recycled material displaces no primary production (without loss of generality, we assume primary production remains at ten each period).[4] Recycled material reaching end of life is handled according to the same rates as primary end-of-life material.
4. Scenario 4 assumes a 100% collection rate with full recovery (no yield loss), demand is not fixed, and recycled material displaces no primary production (primary production again remains fixed at ten each period). Recycled material reaching end of life is handled according to the same rates as primary end-of-life material.

Figure 1 shows the outcome over time for primary production, recycling, and disposal for these four scenarios. Scenario 1 reaches a steady state in time T1 with exactly as much material disposed as is produced each year. Scenario 2 also reaches a steady state in time T1, where five of the ten primary units are collected and the other five disposed. Of the five collected units, four are recycled and one is disposed, for a total of six units disposed each period. Scenario 3 reaches a steady state over time. The amount collected, recycled, and disposed follow geometric series, which, using the values described above, approaches a limit (asymptotes) after about ten periods. Once the new steady state is reached, 6.67 units are recycled and 10 units are disposed each period.[5] The key insight from comparing Scenarios 1, 2, and 3 is that the amount disposed is determined not by collection rates or yield loss, but by displacement. In Scenario 2, four units are displaced, and disposal falls by four units. In Scenario 3, nothing is displaced, and disposal remains the same as in Scenario 1, where nothing is recycled.

Scenario 4 is designed to address the common notion that the way to reduce disposal is to increase collection and reduce yield loss. Scenario 4 demonstrates that, without displacement, perfect collection and recovery lead to a physically unrealistic situation of an infinitely growing market. It is worth pointing out that Scenario 4 not only leads to unrealistic results, but it is based on unrealistic premises: Although we can imagine highly efficient recovery technology in the future, the possibility of creating systems with *zero* loss or quality degradation is far-fetched. Even with more realistic assumptions, if displacement is less than 100%, any collection rate value less than one or any yield loss value greater than zero will result in the long-term outcome of Scenario 3; the values of collection rate and yield loss only determine how quickly the system reaches a new steady state. Thus, with zero displacement, the real-world result will look something like the pattern in Scenario 3, where recycling does not affect disposal—the higher we can push displacement rates, the more reality will start to resemble Scenario 2, where disposal is reduced.

General Equations

The results demonstrated in the scenarios above can be generalized into equations for the mass of waste generation (EOL), primary production (P), collection (C), recycling (R), and disposal (D) in time period n as functions of an original primary

Time period	T_0	T_1	T_2	T_3	…	T_n
Scenario 1						
Primary production	10	10	10	10	…	10
Material recycled		0	0	0	…	0
Material disposed		10	10	10	…	10
Scenario 2						
Primary production	10	6	6	6	…	6
Material collected		5	5	5	…	5
Material recycled		4	4	4	…	4
Material disposed		6	6	6	…	6
Scenario 3						
Primary production	10	10	10	10	…	10
Material collected		5	7	7.8	…	8.33
Material recycled		4	5.6	6.24	…	6.67
Material disposed		6	8.4	9.36	…	10
Scenario 4						
Primary production	10	10	10	10	…	10
Material collected		10	20	30	…	∞
Material recycled		10	20	30	…	∞
Material disposed		0	0	0	…	0

Figure 1 Outcome of four scenarios with varying assumptions about recycling and primary production displacement. "Material collected" refers to material that is collected for recycling; "material recycled" means produced secondary material, adjusted for yield losses. The arrows and percentages are meant to aid the reader in understanding the flows in each time step. Arrows in Scenario 2 show the time step from T0 to T1; arrows in Scenario 3 show the time step from T1 to T2. For example, material collection in Scenario 3 in T2 is calculated as 50% of 10 primary production units (equation (5)) plus 50% of previously 4 recycled units (equation (2)) that is collected again (5 + 2 = 7). The circles in the final column emphasize the amount disposed in the four scenarios.

market size (M), fractional collection rate (c), recycling yield (r), and displacement (d):

$$EOL(n) = \sum_{i=0}^{n-1} [(1-d)rc]^i \, M = \frac{1-[(1-d)rc]^n}{1-[(1-d)rc]} M \quad (1)$$

$$P(n) = M - drcEOL(n) \quad (2)$$

$$C(n) = cEOL(n) \quad (3)$$

$$R(n) = rcEOL(n) \quad (4)$$

$$D(n) = (1 - rc)EOL(n) \quad (5)$$

Note that limited displacement ($d < 1$) turns waste generation and thus all other quantities into geometric sums.[6] The steady-state solution of the recycling system described by equations (1) through (5) is given by the limit of the geometric series; that is, $n \rightarrow \infty$, which yields equations (6) through (10):

$$P(\infty) = M - drc\frac{M}{1-[(1-d)rc]} \quad (6)$$

$$EOL(\infty) = \frac{M}{1-[(1-d)rc]} \quad (7)$$

$$C(\infty) = c\frac{M}{1-[(1-d)rc]} \quad (8)$$

$$R(\infty) = rc\frac{M}{1-[(1-d)rc]} \quad (9)$$

$$D(\infty) = (1 - rc)\frac{M}{1-[(1-d)rc]} = P(\infty) \quad (10)$$

As an example, if M = 100 and the displacement, recycling yield, and collection rates are $d = 0.2$, $r = 0.8$, and $c = 0.5$,

$$P(\infty) = 88,\ EOL(\infty) = 147,\ C(\infty) = 73.5,$$
$$R(\infty) = 59,\ D(\infty) = 88.$$

From these equations, we can derive a general expression for landfill diversion from recycling $\Delta D(\infty)$ by subtracting long-term disposal (which depends on recycling, collection, and displacement rates r, c and d) from the original primary market size (which can be thought of as disposal without recycling, as in Scenario 1):

$$\Delta D(\infty) = M - D(\infty) = M - \frac{1-rc}{1-[(1-d)rc]}M \quad (11)$$

$$\Delta D(\infty) = \frac{drc}{1-(1-d)rc}M \quad (12)$$

Similarly, we can derive a general equation for primary production reduction ΔP by subtracting long-term primary production from the constant primary market size:

$$\Delta P(\infty) = M - P(\infty) = M - \left(M - drc\frac{M}{1-[(1-d)rc]}\right) \quad (13)$$

Table 1 Per-kg production and disposal GHG emissions for example recyclable materials

Material	*GHG emissions per 1 kg primary production (kg CO_2-eq.)*	*GHG emissions per 1 kg landfilled (kg CO_2eq)*	*GHG emissions per 1 kg incinerated (kg CO_2eq)*
PET	2.14–3.27	0.075	2.420
Newsprint	0.119	0.876	1.070
Steel ingot	1.87	0.014	—
Aluminum ingot	8.75–16.5	0.014	—

Emissions data from GaBi 8 Professional Database (Thinkstep 2017) and Wang and colleagues (2012). Characterization using Traci 2.0 (Bare 2011). Newsprint emissions include biogenic carbon. Incineration modeled as cradle-to-gate waste-to-energy plant; electricity and steam coproducts are not allocated.
CO_2eq = carbon dioxide equivalent; GHG = greenhouse gas; kg = kilograms; PET = polyethylene terephthalate.

$$\Delta P(\infty) = \tfrac{drc}{1-(1-d)rc}M = \Delta D(\infty) \tag{14}$$

The critical insight from these equations appears in equations (12) and (14), where the reduction in disposal is a function of d in the numerator. Thus, if there is no primary production displacement ($d = 0$), there is no reduction in disposal. Comparing equations (12) and (14), we see that the reduction in disposal is equivalent to the reduction in primary production.

For example, using the values above,

$$\Delta D(\infty) = \Delta P(\infty) = \frac{0.2 \cdot 0.5 \cdot 0.8}{1 - 0.8 \cdot 0.8 \cdot 0.5} \times 100 = \frac{8}{0.68} = 12 \tag{15}$$

which shows that primary production is reduced by 12 units, which results in landfill reduction of the same size. The recycled units that don't displace primary production, here 59 − 12 = 47, have no impact on landfill reduction.

Significance for Life Cycle Assessment Methodology

The previous section argues that if recycling fails to displace primary production, it also does not prevent disposal. However, traditional end-of-life models—for instance in LCA—have typically assumed that recycling prevents landfill. They also typically assume recycling prevents primary production one to one. This means that traditional models overestimate the benefit of recycling, thereby underestimating the total impacts of the product system. But by how much? And how should we improve our models to account for these insights?

The amount of disposal diversion from recycling under the (incorrect) assumption that all recycled material is diverted from landfill can be expressed as

$$\Delta D_e = rcM \tag{16}$$

The amount of landfill diversion from recycling under the correct assumption (that only what is displaced is diverted) is shown in equation (12). The magnitude of the error introduced by making the incorrect assumption can be computed by subtracting equation (12) from equation (15):

$$Error = \Delta D_e - \Delta D(\infty) = rcM - \tfrac{drc}{1-(1-d)rc}M \tag{17}$$

For example, if $r = 0.8$, $c = 0.7$,and $d = 0.5$, the error is roughly 17% of the primary market size M. The lower limit for the error is zero, which occurs when $d = 1$; the upper limit is rcM, which occurs when $d = 0$. Thus, the higher the recycling yield and collection rate, the more important it is to correctly model disposal flows; as recycling and collection rates approach 100%, the error size approaches M.

The error expressed in equation (16) represents the size of the flows that ought to be modeled as going to landfill or incineration but are in fact ignored. From equation (14), we know this is also the quantity of primary production that is improperly being assumed to be displaced. The importance of this error in terms of underestimating environmental impacts depends on the per-unit impacts of the disposal process (in the case of improperly ignoring disposal) and the production process (in the case of improperly assuming full displacement). These per-unit impacts, of course, vary by material and disposal or production technology. Table 1 shows example unit greenhouse gas (GHG) emissions of production, landfill, and incineration for three exemplary recyclable materials: PET, newsprint, and aluminum. From table 1, we can see that for PET, steel, and aluminum, the error introduced by improperly accounting for landfill is smaller than that of improperly assuming full primary production displacement. Newsprint has lower production GHG emissions due to biogenic sequestration and higher landfill emissions from biodegradation. Unfortunately, the status quo in LCA is to not properly account for post-recycling disposal *and* to blindly assume 100% primary production displacement, so typically the two types of errors are compounded.

Conclusions

Our argument, in many ways, should be unsurprising. On the most basic level, we are merely pointing out that real-life material recovery systems are technically imperfect, so that some collected material will still be landfilled. Building on this, we are simply illustrating the principal of mass conservation in a closed system by showing that everything that is created, no matter how many times it might be cycled through the economy, must eventually be disposed. Recycling can never *prevent* end-of-life disposal, it can merely *delay* it. This leads us to an obvious but surprisingly underappreciated conclusion:

The only way to reduce the amount of material we landfill or incinerate is to reduce the amount we produce in the first place.

What is not made need not be thrown away. The *only* way recycling can reduce the amount we produce is by displacing primary production. Thus, the *only* way recycling can reduce disposal is by displacing primary production.

While our thesis should not be surprising, it should change the way we think about the benefit of recycling. Specifically, it should now be clear that the dual benefits of primary production displacement and landfill avoidance are, in fact, one and the same. If recycling displaces primary production, it not only avoids the impacts of that production but also reduces the total amount of material that must eventually reach the end of its life. Additionally, we should adjust our end-of-life models to acknowledge that only part of what is recycled—the part that avoids primary production—will reduce disposal. Total impacts of a system with recycling are correctly calculated as:

$$E_{net} = E_{prim} + E_{rec} - \frac{drc}{1-(1-d)rc}(E_{prim} + E_{disposal}) \tag{18}$$

If $d = 1$, the quantity $\frac{drc}{1-(1-d)rc}$ reduces to rc, which represents standard practice but underestimates E_{net} if $d \neq 1$.

Our argument should also further highlight the primacy of displacement in recycling policy and research. We should focus our policy and scholarly efforts on finding and implementing ways to ensure higher displacement rates. To that end, we should evaluate potential recycling technologies or policies not on their ability to increase collection rates or maximize technical properties but on their ability to maximize displacement rates. For instance, it may be the case that the public advertising emphasis on recycling encourages more use of recyclable single-use products because consumers believe that recycling will erase the negative impacts of using them. If this is true, policy efforts may be better directed at discouraging use of single-use products (e.g., recent movements against disposable drinking straws) rather than encouraging their collection for recycling. The primary environmental goal should be reducing environmental impacts by reducing primary production; the ability of recycling to accomplish that goal is uncertain at best; policy efforts will likely be more effective addressing the problem upstream rather than downstream.

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Notes

1. We have glossed over the occasional market-based arguments for recycling. While these exist, the stronger evidence points to the increased costs of recycling. Often, proponents of recycling use economic arguments as a thin justification for an environmentally based goal rather than reasons in themselves (Ackerman 1997).
2. It is typically assumed that recycled materials displace primary counterparts. However, it is also possible to assume that recycled material displaces production of a different material (Weidema 2003). For instance, recycled plastic speed bumps or park benches may displace asphalt or wood.
3. Note that this is not a statement about entropy or thermodynamic limits, which have been demonstrated to be unrelated to the utility of recycled materials (Ayres 1999; Kovalev 2016). Rather, this is about the deterioration of technical properties and the dispersion of materials into unusably small particles or into impractical-to-recover locations or formats.
4. Setting the displacement rate equal to zero means that increased recycling does not affect primary production. However, primary production might increase or decrease over time in response to other economic factors. For simplicity, we assume it remains fixed at ten units, though the scenario is compatible with any other assumption about the behavior of primary production. The key assumption in Scenario 3 is simply that primary production levels are unaffected by changes in secondary production.
5. The fact that primary production remains at 10 units and 6.67 additional units of secondary material are produced each period in the long run means that recycled material has not cannibalized primary production but has increased the overall amount of material used, expanding the material into new uses, applications, or markets. It is worth noting that the extra 6.67 units of secondary production have impacts of their own. In this scenario, we would see both the primary production impacts of 10 units *plus* the comparatively lower (but significant) impacts of secondary production. Thus, because recycling does not displace primary production, the recycling in Scenario 3 actually increases impacts relative to the no-recycling Scenario 1. The general lesson is that if recycling sufficiently increases overall production, it can create more damage than benefit (Zink et al. 2015).
6. This is not to be confused with the geometric sum that forms when a batch of primary material is followed through recurring recycling cycles, and the amounts of recycled material from each cycle are added together (see, e.g., Nyland et al. 2003). As we have argued elsewhere, such a way to think about and account for multiloop recycling is intuitive but flawed (Geyer et al. 2015).

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